A Plan for Low Energy Science at the 88-Inch Cyclotron in the Next Decade

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“Plans are useless, but planning is indispensable”.

- Dwight D. Eisenhower

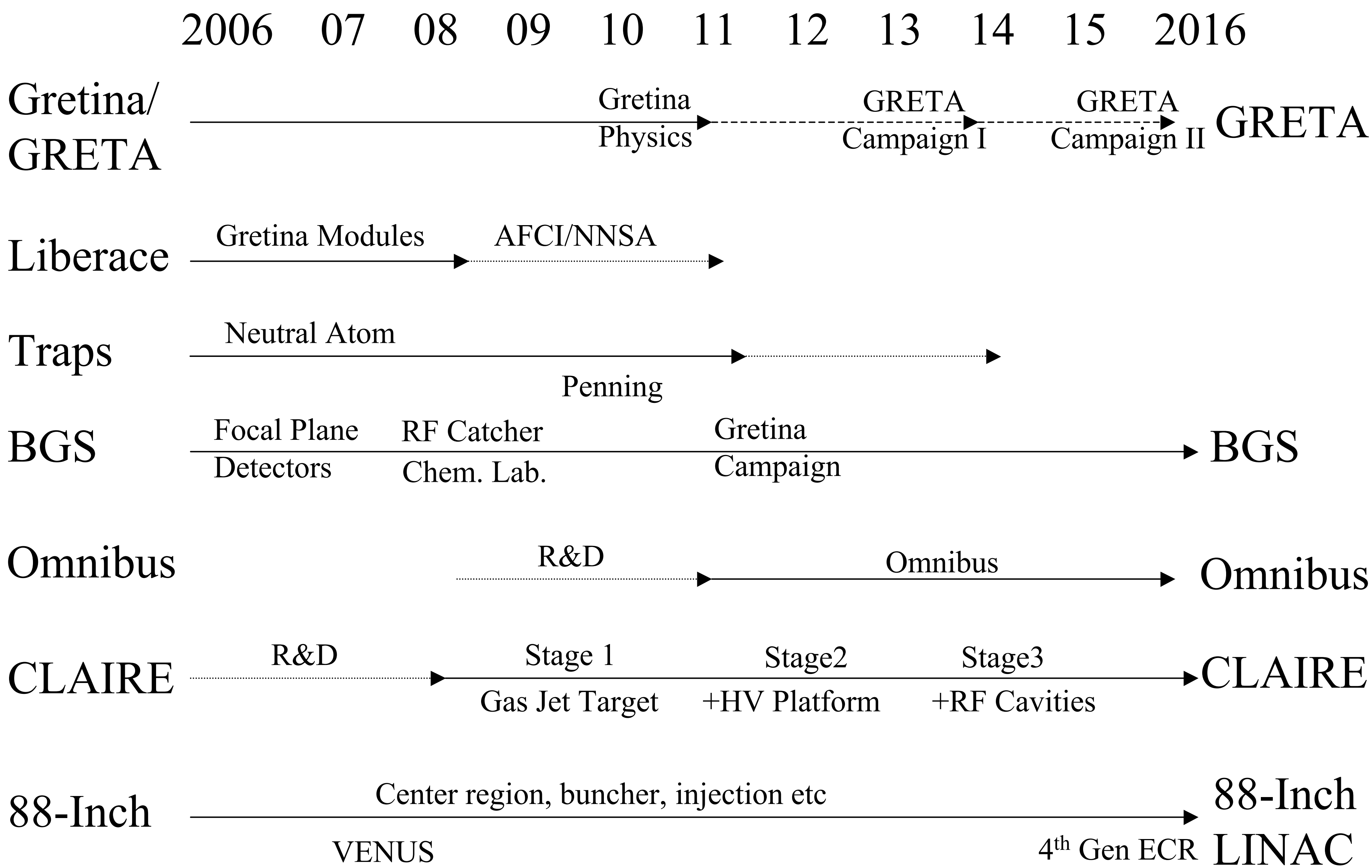
"A good plan violently executed now is better than a perfect plan next week".

- George S. Patton

"Life is what happens to you while you are busy making other plans".

- John Lennon

A Plan for the Next Decade: Timeline



Advantages From Operation of 88-Inch

- BASE Program
  - Vital to defense and aerospace communities

- In-house Science Programs
  - Unique heavy element research effort
  - Applied (surrogate and n-beam) work (AFCI and Defense)
  - LIBERACE science: structure, reactions, astrophysics
  - Home to fundamental symmetries program
  - Home to GRETINA/GRETA development
  - Home to VENUS ion-source development

- Training post-docs and students.
  - Connections to UCB Physics, Chemistry, and Nucl. Eng.

- Retention of broad stable beam capability.
  - Complementary role in the radioactive beam era

In-House Low Energy Science Program: 2016

- Upgraded 88-Inch able to host scientific and applied programs including a stable-beam program with GRETA (full 4π array).

- 88-Inch is home to two world-leading large acceptance separators, BGS and Omnibus. Unique scientific programs:
  - a) Heavy element science
    - Chemistry and atomic properties
    - Transfermium spectroscopy (prompt and delayed)
    - Mass measurements
  - b) Far-from-stability studies complementary to RIB efforts
    - Gamma-ray studies of n-rich nuclei via DIC
    - Decay studies (and tagging) of rare isotopes

- CLAIRE: National accelerator facility for nuclear astrophysics with low-energy high-intensity beams. Allied with DUSEL.

FY07/08

a) *Extensive program of Nuclear Structure experiments, defense and AFCI work.*
LIBERACE will be coupled with GRETINA modules. (LDRD funded $300K).
Extend Si detection to ~4π by adding Si box to existing annular set-up. $50K.

b) *New effort on transfermium decay spectroscopy (especially high-K isomers).*
Focal plane detectors (especially a DSSD) for BGS. $50K.

c) *Extended effort on physics beyond the Standard Model.*
New neutral atom trapping effort on ^{18,19}Ne. $150K.

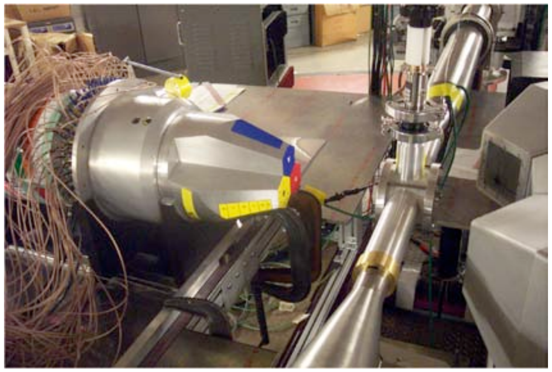
d) *New generation of heavy element chemistry experiments.*
Pu targets and dedicated chemistry laboratory. BGS as pre-separator. $250K.

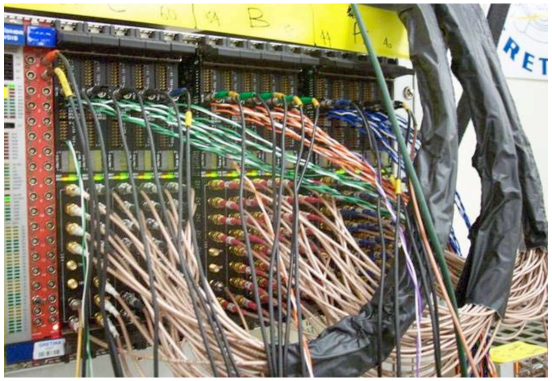
e) *New astrophysics program looking towards DUSEL.*
R&D for CLAIRE. (LDRD funded $220K).

Some examples from the above…

LIBERACE Upgrades

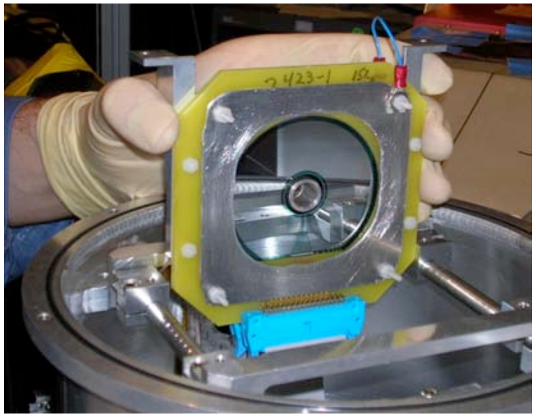
a) Add GRETINA Modules

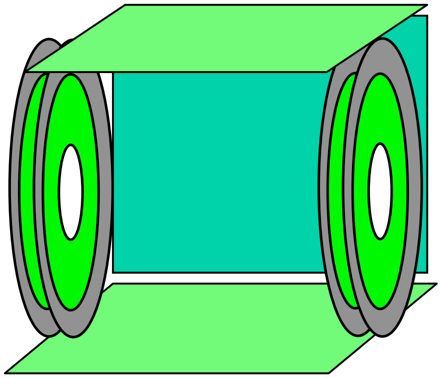




• Digitial Signal Processing (DSP) for Clovers and Si detectors
• Add GRETINA Modules
• Higher E_γ efficiency (high-E_γ)

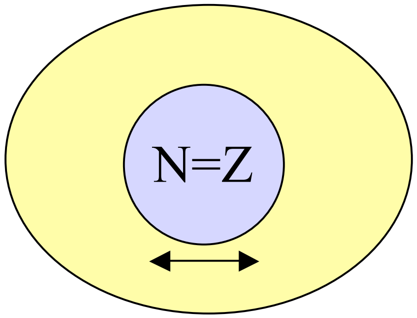
b) STARS and STRIPES



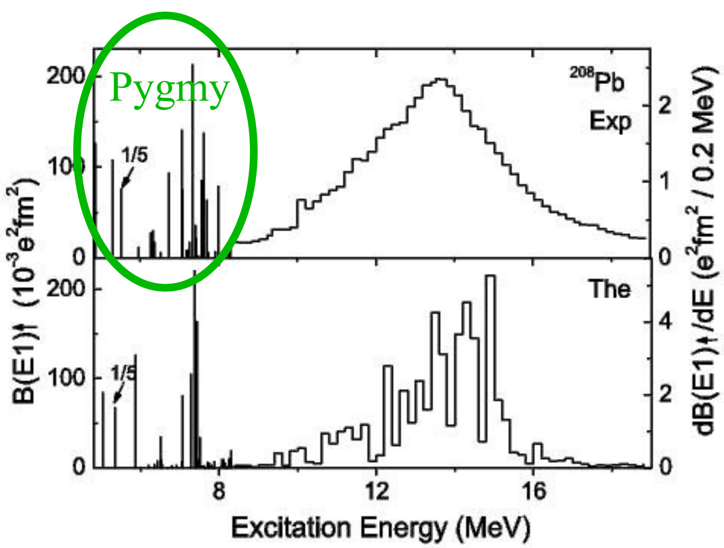


• Currently annular Si detectors (STARS)
• Add planar Si detectors box (STRIPES)
• Increased particle detection efficiency

Fine Structure of Pygmy Resonances

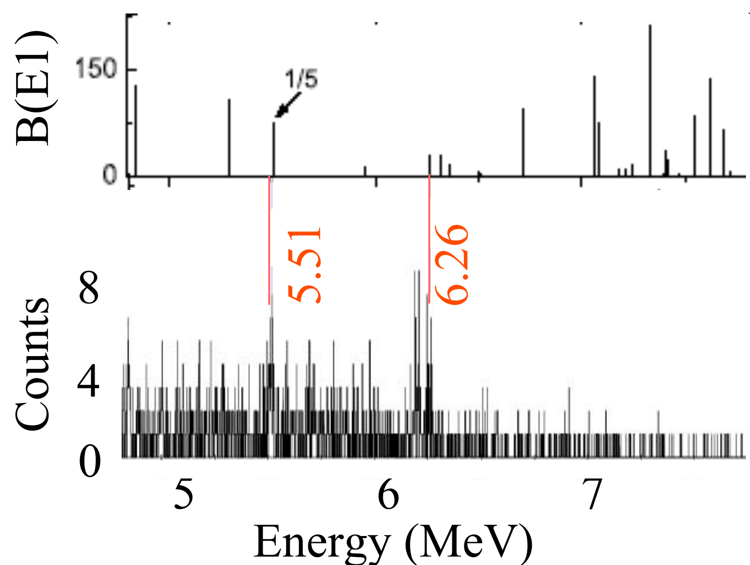


- Soft dipole mode
- Small fraction of E1 strength
- Usually studied in (γ, γ')



N. Ryezayeva et al, PRL 87 272592 (2002)

- Using the ^{208}Pb(^{17}O, ^{17}O') reaction with LIBERACE+STARS
- Population and decay of different states compared with (γ, γ') experiments
- Test experiments (2005/06) revealed potential of method (see below).
- Need large increase in statistics
  → Cooling of Si detectors (> Dec 2006).
  → **Add GRETINA modules**



NRF deduced E1 components (10^{-3} e^2fm^2)

Spectrum from LIBERACE experiment.

M. A. Deleplanque et al.

^{16}C - Cracking the Egg

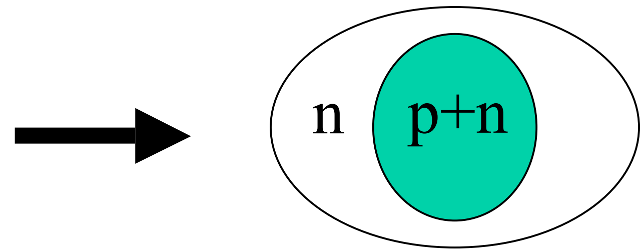
Results from RIKEN

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

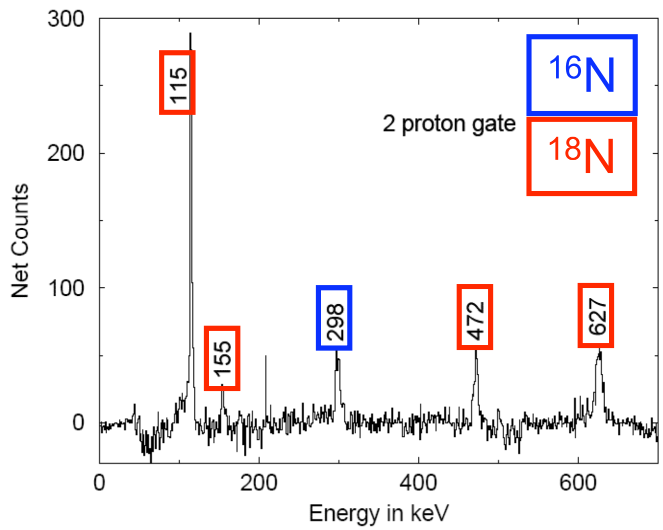
Anomalously Hindered $E2$ Strength $B(E2; 2_1^+ \rightarrow 0^+)$ in ^{16}C

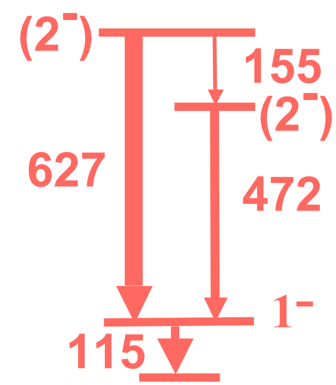
PHYSICAL REVIEW C **73**, 024610 (2006)

Neutron-dominant quadrupole collective motion in ^{16}C



- We can study ^{16}C via the ^{11}B(^{7}Li,2p) reaction with LIBERACE+STARS
  → Measure lifetime via Doppler shift techniques and deduce B(E2)
- Shown utility of 2p-evaporation studies of sd-shell light nuclei already
- ^{9}Be(^{11}B,2p)^{18}N to resolve anomalous 1- isomeric decay





M. Wiedeking et al.

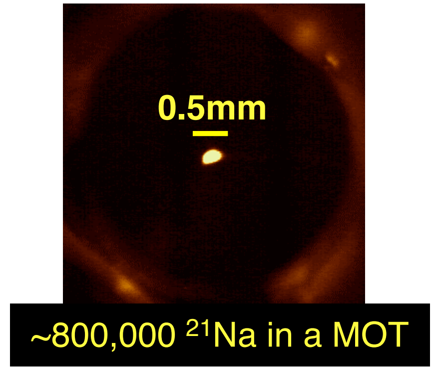
~4π p-detection efficiency of STARS+STRIPES ideal for such studies

β-ν Correlation Measurements

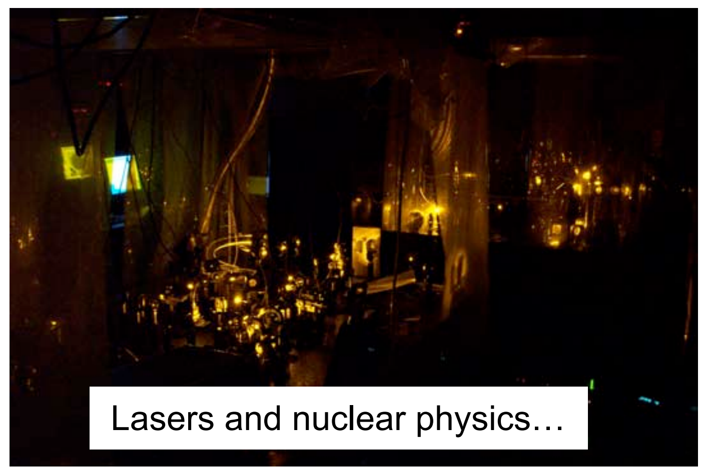
Currently: laser trapping of ^{21}Na for precision electroweak tests

Laser trapped samples are:
- Cold
- Isotopically pure (contaminant-free)
- Held in vacuo: no scattering (not very dense)
- Polarizable

Ideal source for:
Full kinematic detection of a beta decay



Beyond Standard Model Physics search:
- Non "Vector minus Axial Vector" couplings
- New Scalar Bosons
- Second class currents from quark mass hierarchy
- Massive sterile neutrinos
- Left-Right symmetric models
- Sleptons…

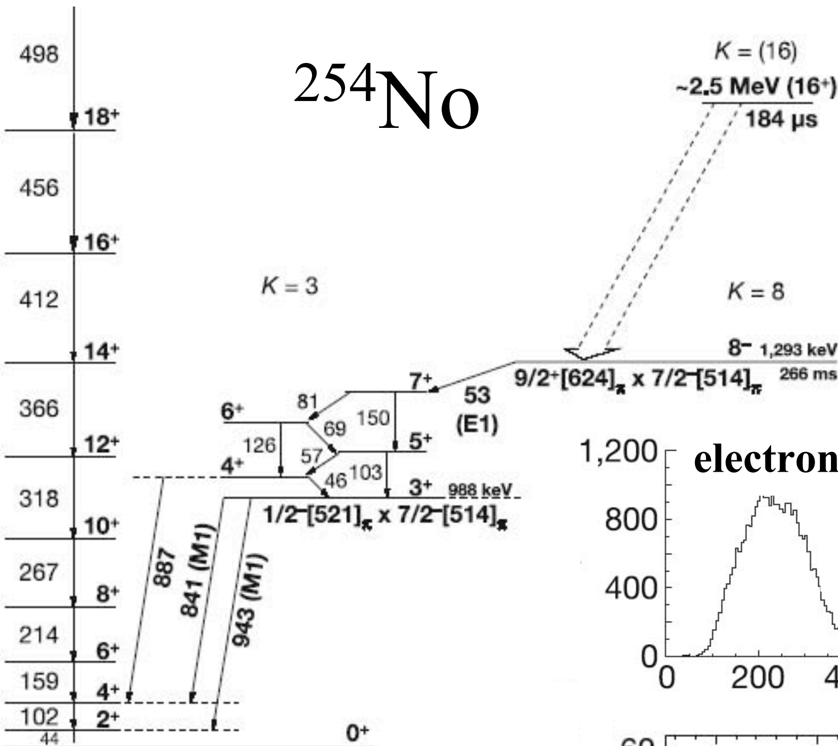


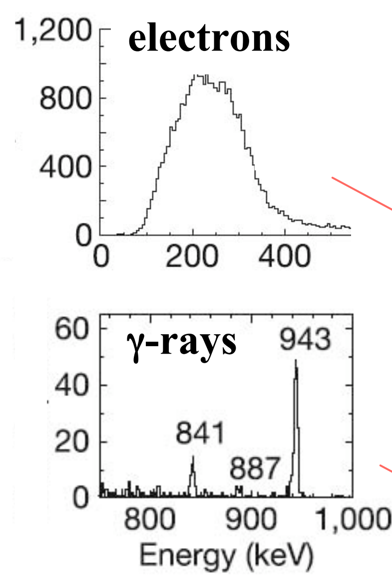
Future: ^{18,19}Ne "cleanest" test for scalar or tensor currents outside Standard Model

BGS Focal Plane Studies: K-Isomers in Transfermium Nuclei

Nuclear isomers in superheavy elements as stepping stones towards the island of stability

R.-D.Herzberg et al., Nature 442 (2006) 896, S.Tandel et al., Phys. Rev. Lett. 97 (2006) 082502





^{48}Ca+^{208}Pb at 219 MeV
RITU+GREAT – 10 days

- BGS superior heavy element separator to either FMA or RITU
- Clean tag on isomer decays from conversion electrons in a DSSD.
- Clovers/LEPS detect gammas.

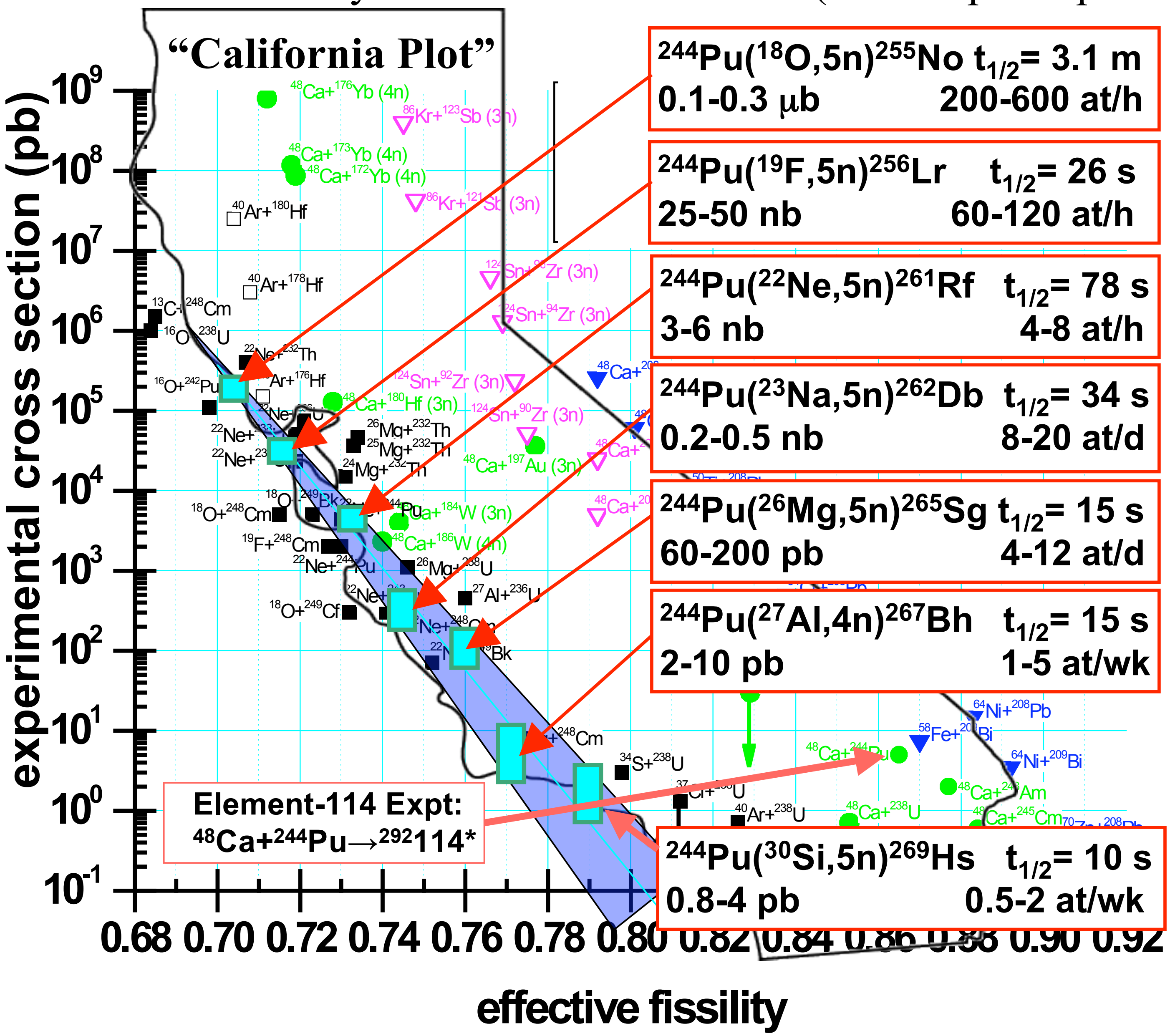
BGS Rates

Target = 500 μg/cm²
Current = 0.7 pμA
Chopping factor = 0.5
Efficiency (BGS)=0.6
Cross section = 2μb
→ 6 x 10^5 recoils at focal plane /day
Fraction ms-isomer=0.5
Efficiency (DSSD)>0.5
Efficiency (Ge)>0.05
→ >7500 γ’s/day

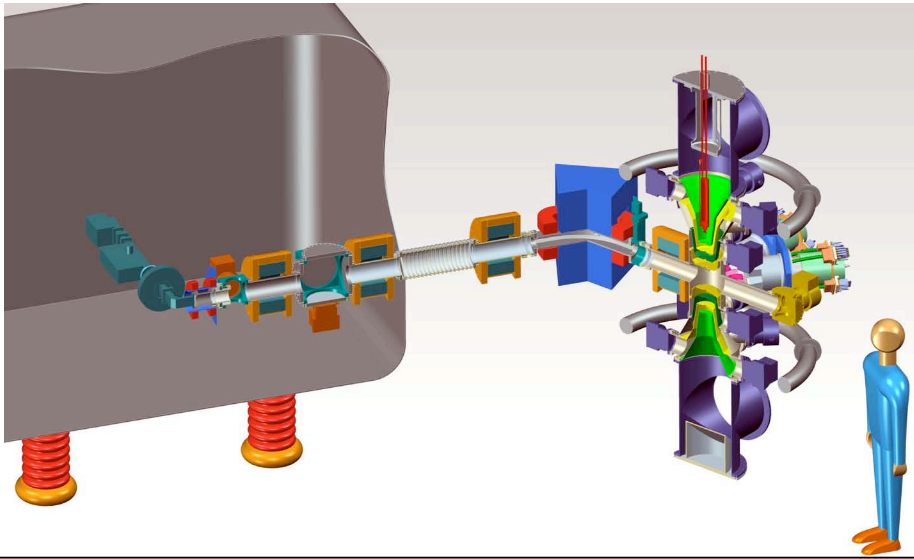
Heavy Element Experiments with Pu Targets

Pu targets allow access to longer-lived neutron-rich isotopes

A dedicated chemistry lab is needed near BGS (used as pre-separator)



CLAIRE: A National Accelerator for Nuclear Astrophysics



• Meet the need identified in last LRP of a "…dedicated, high intensity (~mA), low-energy (<3MV), accelerator.."

• Required in order to understand stellar evolution especially H and He burning.

The Stages of CLAIRE

1) *Gas jet target* (~$10^{18\text{-}19}$ particles/cm^2).
Beams from 88-Inch to measure "γ-process" reactions: e.g., ^{96}Ru(α,γ), ^{124}Xe(α,γ), ^{136}Ce(α,γ)

2) *Add HV Platform*
1^+ ion source, analyzing magnet, focusing optics. Provide intense light-ion beams for measurement of key H and He burning reactions.

3) *Add RF Cavities and ECR Source*
Reactions in CNO and Ne-Na-Al Cycles.

Two examples of key reactions

^{3}He(^{4}He, γ)^{7}Be

- Crucial to understanding of solar neutrino flux.
- Needed to 1% accuracy in region of Gamow window

^{12}C(α, γ)^{16}O

- Determines fate of intermediate mass stars (black hole vs. neutron star).
- Fixes C/O ratio which influences all later nuclear burning stages.

Strong Connection with DUSEL (proposal for gas-jet target)

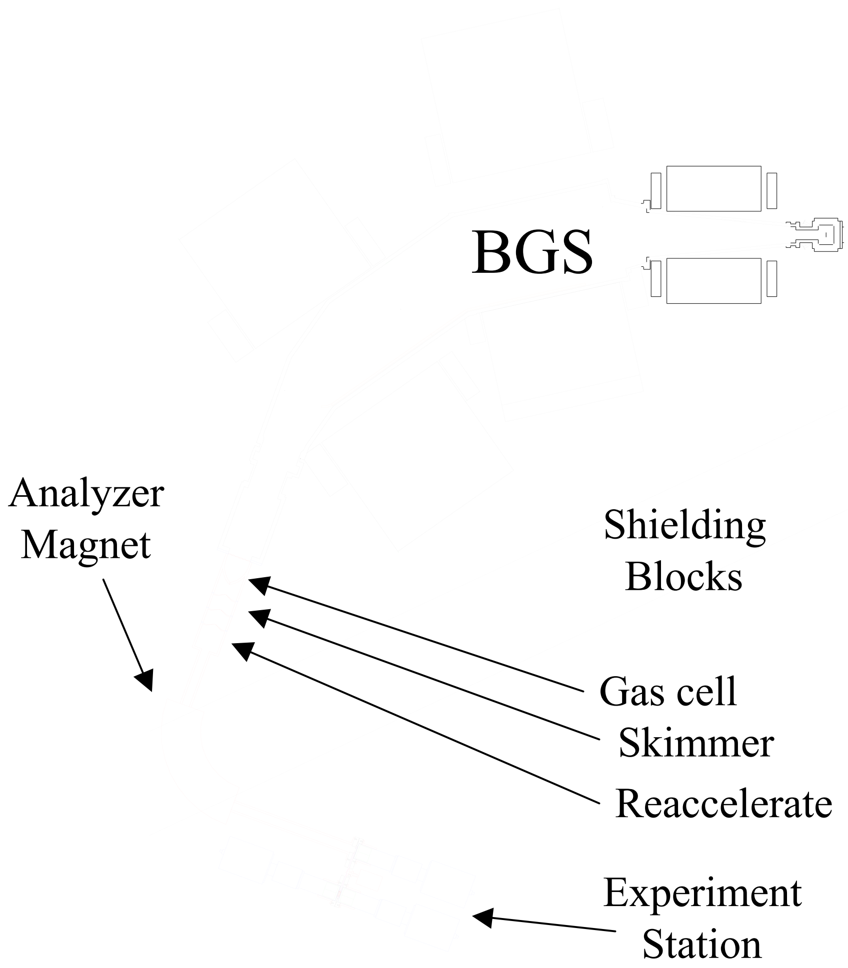
FY09/10

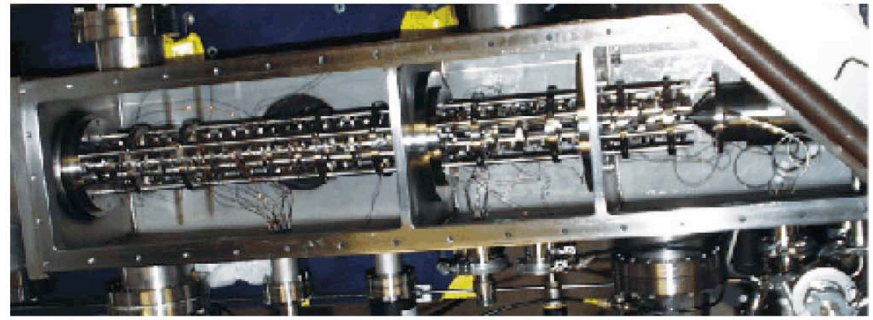
a) *Decay spectroscopy in low background environment. Investigate SHE.*
RF-Catcher built and coupled to BGS. $200K.
Analyzer magnet for mass identification of SHE. $180K.

b) *The Omnibus: unique device for heavy element and far-from-stability studies.*
R&D for Omnibus large acceptance spectrometer.

c) *Investigations of γ-process reactions in inverse kinematics.*
CLAIRE Stage 1 – gas-jet target using beams from the 88-Inch. $700K.

RF Catcher





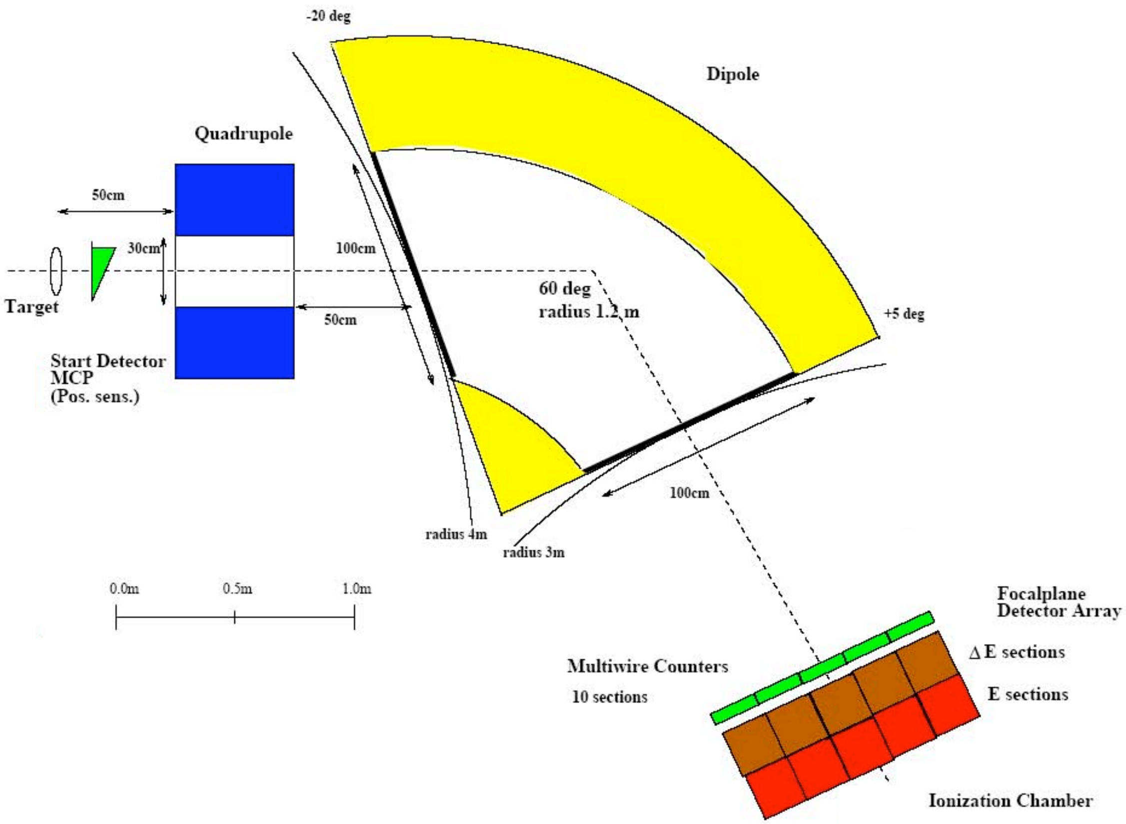
"The Argonne Catcher"

- Reaction products separated from beam by the BGS
- Stopped in high-purity He gas cell – retain 1^{+} charge
- RF field pushes ions towards exit where they are skimmed
- Re-accelerated to moderate potentials (10kV), mass separate.

- Decay studies in low background environment
- Chemistry studies on isotopes with > ms lifetimes
- Mass identification of heaviest atoms (analyzer magnet)

Omnibus

Concept: A superconducting, dual-mode, large-acceptance spectrometer.
Mode 1: Gas-filled "better than BGS" separator.
Mode 2: Gas-less "PRISMA-like" spectrometer.



Solid Angle	Ω~80msr
Momentum Acceptance	$\sim \pm 10\%$
A Resolution	$\frac{\Delta A}{A} \sim \frac{1}{300}$
Z Resolution	$\frac{\Delta Z}{Z} \sim \frac{1}{60}$
Rotation about target	$-20^o \le \theta \le 130^o$

- Study nuclei far-from-stability populated in deep-inelastic reactions.
- A large-acceptance spectrometer of the type needed at future FRIB.

GRETINA/GRETA+Omnibus: Far-From-Stability Studies

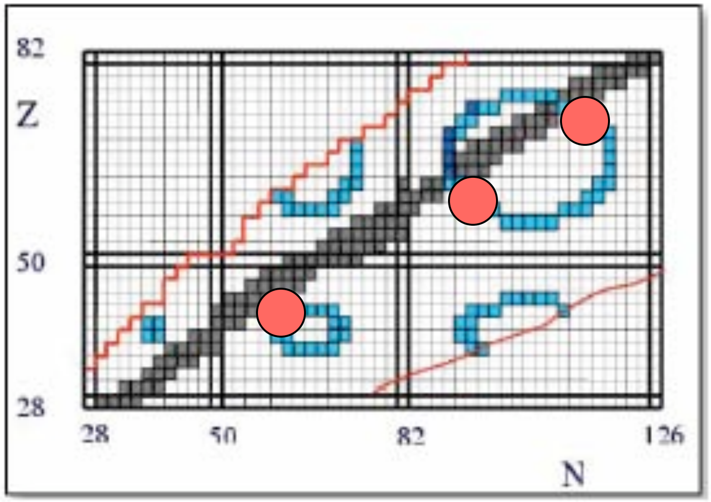
- Omnibus in gas-less mode allows Z and A identification ($\Delta Z/Z \sim 1/80$, $\Delta A/A \sim 1/300$) of species formed in deep-inelastic reactions (non-selective population of high-I states).
- GRETA allows us to extend reach for γ-spectroscopy by several more neutrons.
- Complementary to radioactive-beam studies of nuclei far-from-stability

Some Physics Examples

- Structure of nuclei near doubly magic (Approaching ^{78}Ni and ^{132}Sn).
- Stability of shell gaps in n-rich nuclei (Recent controversy in $^{52-54}$Ca).
- Highly deformed states in n-rich S-Ar (Overlap of theories).
- New exotic excitation modes (Pygmy resonances in Ca isotopes)
- Shape evolution and critical-point nuclei in n-rich regions. (N-rich Zr-Mo, Ce-Nd, and Er-Yb)

Loci of $P = \dfrac{N_p N_n}{N_p + N_n} \sim 5$

Near stability this reflects rapid change from vibrational to rotational behavior



Will this hold true in n-rich nuclei?

FY11/12

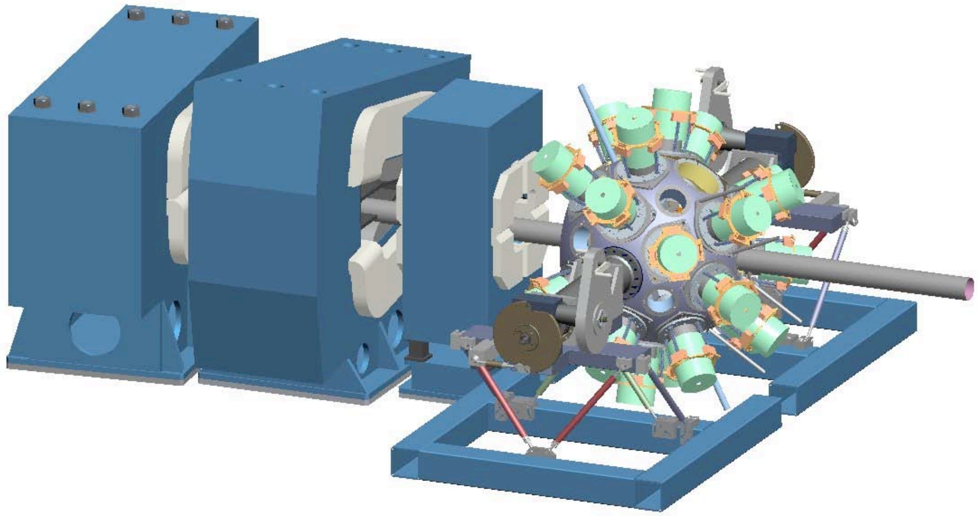
a) *High-precision mass measurements and atomic physics of heavy elements.*
Penning trap combined with RF catcher at end of BGS. $700K.

b) *Transfermium spectroscopy with most powerful set-up conceivable.*
Gretina coupled to BGS at target position. $250K.

c) Construction of Omnibus. $5000K.

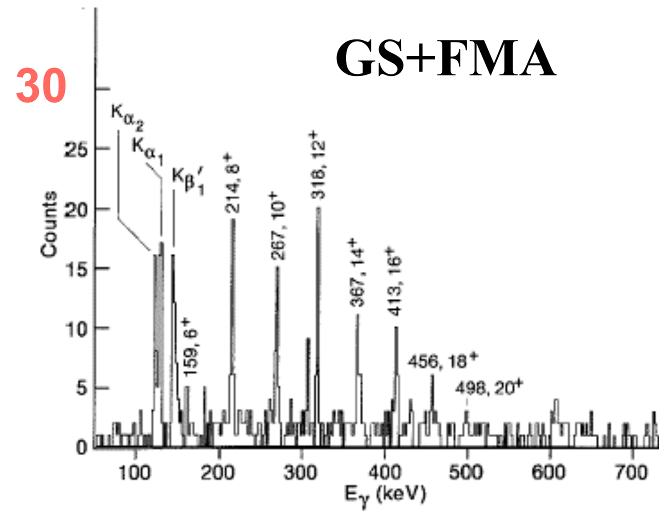
d) *High intensity (~0.1 A) light ion beams for H and He burning experiments.*
CLAIRE Stage 2 – HV platform with gas-jet target. $700K.

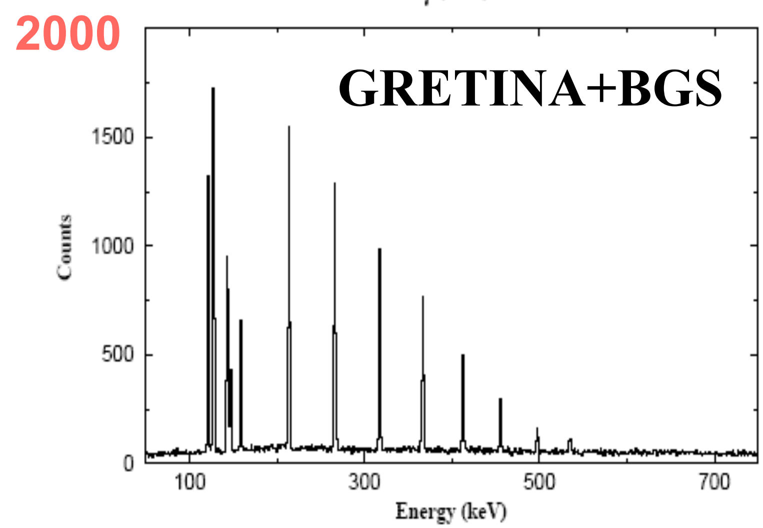
BGS+GRETINA: Transfermium Spectroscopy



$^{48}Ca+^{208}Pb \rightarrow ^{254}No+2n$

$\sigma \sim 2\ \mu b$





- New generation of prompt transfermium gamma-ray spectroscopy.
- Detailed γ-γ spectroscopy on even-even Z>100 nuclei possible.
- γ-spectroscopy on odd-A nuclei
- γ-spectroscopy of Rf (Z=104) possible ($^{50}Ti+^{208}Pb \rightarrow ^{256}Rf+2n$ with $\sigma \sim 20$ nb).

Single-particle orbits same as those in predicted spherical SHEs

FY13/14

a) *Omnibus in gas-filled mode used for heavy element physics and chemistry.*
First scientific campaigns with Omnibus.

b) *GRETA+Omnibus in gas-less mode for DIC experiments on n-rich nuclei.*
GRETA on construction path. Host 2π array (combined with Omnibus).

c) *R&D for CLAIRE stage 3 to study of CNO and NeNa cycles with heavier beams.*
CLAIRE Stage 3 – ECR source and RF cavities added.

FY15/16

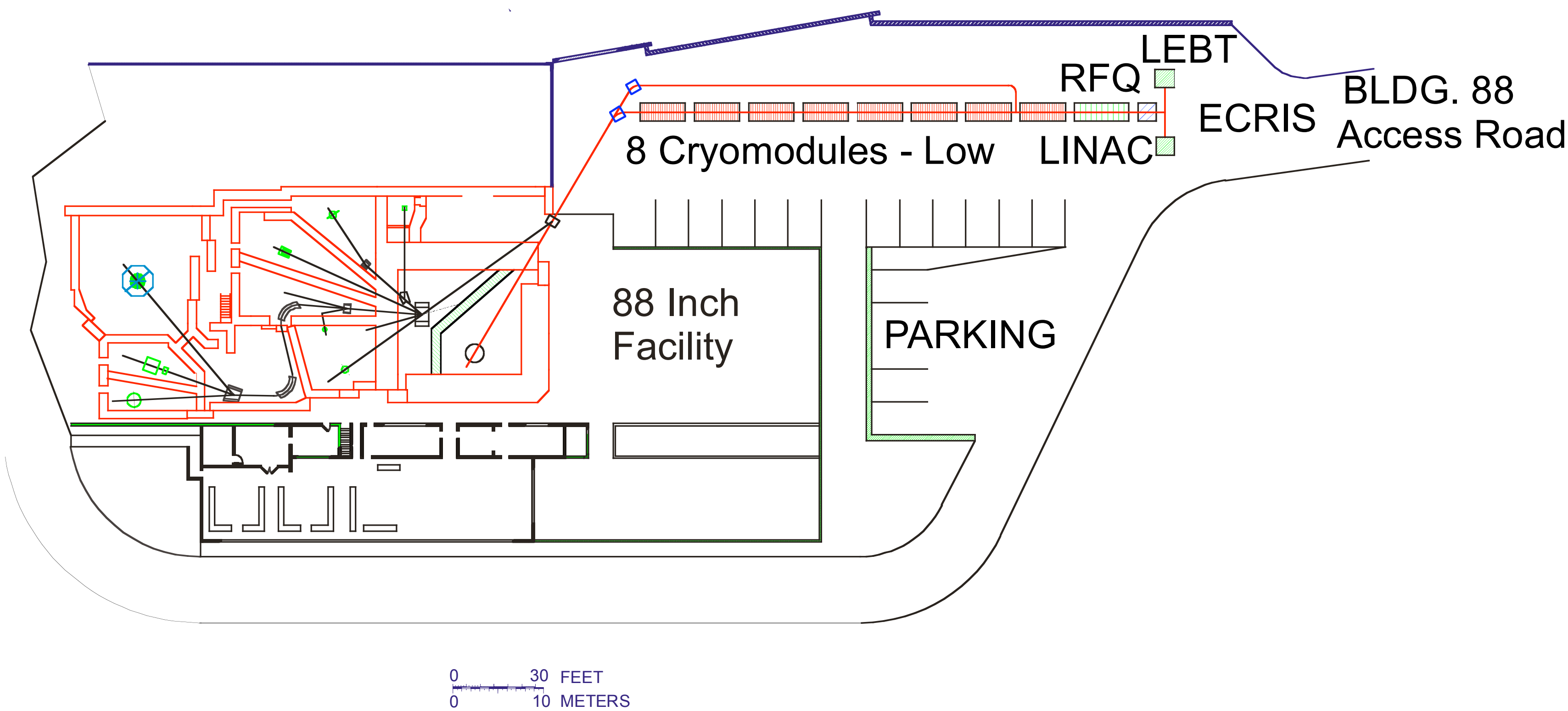
a) *CLAIRE is National Accelerator Facility for nuclear astrophysics*
Add RF cavities to CLAIRE to create high intensity LINAC.

b) *Omnibus and BGS used for program of heavy element and far-from-stability studies.*
Omnibus and BGS are versatile large acceptance spectrometers.

c) *Full program on hyperdeformation, transfermium spectroscopy, new excitation modes in n-rich nuclei, etc*
Host completed 4π GRETA for stable beam campaigns.

d) *Host scientific and applied programs at 88-Inch.*
88-Inch remains versatile stable beams machine.

A Possible Road to a High-Intensity LINAC



A Plan for the Next Decade: Timeline – Growth of Manpower

2006 07 08 09 10 11 12 13 14 15 2016

Gretina/ GRETA — Gretina Physics — GRETA Campaign I — GRETA Campaign II — GRETA

Liberace — Gretina Modules — AFCI/NNSA

Traps — Neutral Atom — Penning

BGS — Focal Plane Detectors — RF Catcher Chem. Lab. — Gretina Campaign — BGS

NEED SCIENTIST (TRANS-ACTINIDE PHYSICS)

Omnibus — R&D — Omnibus — Omnibus

NEED SCIENTIST (ASTROPHYSICS)

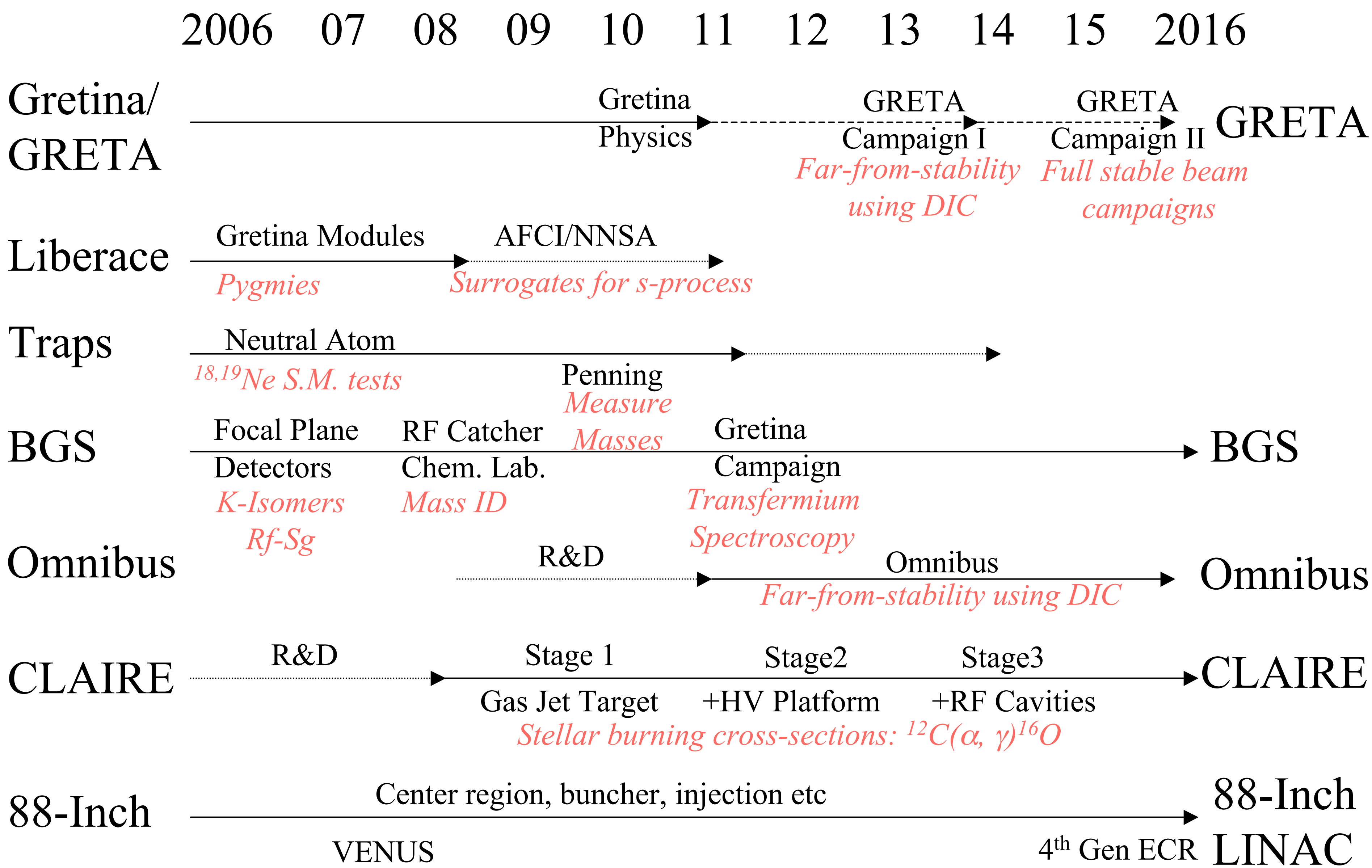
CLAIRE — R&D — Stage 1 Gas Jet Target — Stage2 +HV Platform — Stage3 +RF Cavities — CLAIRE

NEED ACCELERATOR PHYSICIST

88-Inch — Center region, buncher, injection etc — VENUS — 4th Gen ECR — 88-Inch LINAC

NEED ENGINEERS, TECHNICAL AND MECHANICAL SUPPORT, AND POSTDOCS

A Plan for the Next Decade: Timeline – Science Topics



Mapping to DOE/NSAC Milestones

Year	Milestone / 88-Program / Experiment
2006	Measure changes in shell structure and collective modes as a function of neutron and proton number from the proton drip line to moderately neutron-rich nuclei. LIBERACE program using light-ion fusion-evaporation, transfer, and incomplete fusion. Example – lifetime measurement of excited states in ^{16}C, the egg nucleus.
2007	Measure properties of the heaviest elements above Z~100 to constrain and improve theoretical predictions for super-heavy elements. BGS program on heavy element production, structure, and chemistry. Example – K-isomer studies at BGS focal plane up to Sg (Z=106) nuclei.
2009	Extend spectroscopic information to regions of crucial doubly magic nuclei far from stability such as Ni-78. Deep-inelastic reactions using GRETINA/OMNIBUS and intense beams from VENUS. Example – $^{238}U+^{48}Ca$ to investigate N=32,34 sub-shells and push towards doubly magic ^{60}Ca.

Mapping to DOE/NSAC Milestones

Year	Milestone / 88-Program / Experiment
2010	Complete initial measurements with the high resolving power tracking array,GRETINA, for sensitive studies of structural evolution and collective modes in nuclei. Use GRETINA modules and full 1π-array for physics campaigns at 88-Inch. Example – pygmy resonance structure in ^{208}Pb from H.I. inelastic scattering. Example – transfermium spectroscopy (prompt)up to Rf (Z=104) using BGS.
2010	Reduce uncertainties of the most crucial stellar evolution nuclear reactions (e.g. $^{12}C(\alpha, \gamma)^{16}O$) by a factor of two, and others (e.g., MgAl cycle) to limits imposed by accelerators and detectors. Development and use of CLAIRE (Stages 2 and 3) Example – direct measurement of $^{12}C(\alpha, \gamma)^{16}O$.
2011	Measure neutron capture reactions, including s-process branch-point nuclei, to constrain s-process isotopic abundances. Surrogate techniques developed with LIBERACE for AFC studies (currently, deducing n-induced actinide cross-sections reactions). Example – $^{153}Gd(n, \gamma)$ determined from surrogates such as $^{154}Gd(\alpha, \alpha')$ and $^{155}Gd(^{3}He, \alpha)$

Plan Rests Heavily on 88-Inch Operations

• Current funding for 88-Inch will mean rapid end to science program at the accelerator.

• Requested funding brings us to “sustainable operation”.

• Scientific plan requires upgrades and improvements.
(e.g. coupling VENUS to 88-Inch to give full range of intense heavy-ion beams for heavy element research).

• Projects like CLAIRE and Omnibus require increased manpower and technical support (accelerator physicist, engineers, techs…)

• We want to host “National Facility”-scale scientific programs.
(GRETINA/GRETA, BGS/Omnibus, CLAIRE…)

Summary

- Developed a strong scientific vision for the next decade
- Aligned with current priorities of the National Low Energy Program
- 88-Inch is central to the plan
- Providing an essential stable beam capability in the U.S.
  - Vital to the BASE and applied programs
  - Unique heavy element research effort
  - New opportunities in nuclear structure
  - Training the next generation
- Developing new facilities and apparatus for U.S. nuclear science
  - GRETINA/GRETA
  - BGS/Omnibus
  - CLAIRE

"Give us the tools and we will finish the job!"